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Theoretical status of the CKM Matrix

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Abstract

In this talk I review the current status of the CKM matrix. A special emphasis is also given to several discrepancies between experiments and the standard model at the level of about three standard deviations. Recent results that appeared after FPCP2011 are also included in the discussion.

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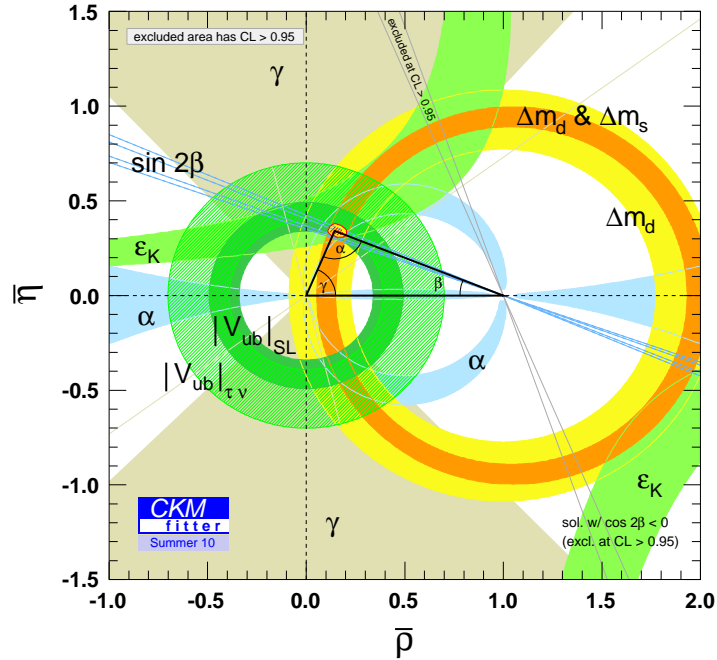
The Ninth International Conference on
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(FPCP 2011)
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1 Introduction

The Cabibbo-Kobayashi-Maskawa-matrix [1, 2] describes flavor transitions in the quark sector. Its elements have been investigated in the last years in detail in particular by the PDG [3], the HFAG [4] and the collaborations CKMfitter [5] and UTfit [6]. A recent fit [7] gives e.g. the following values for the CKM matrix

$$V_{CKM} = \begin{pmatrix} 0.97426 \pm 0.00030 & 0.22545 \pm 0.00095 & 0.00356 \pm 0.00020 \\ 0.22529 \pm 0.00077 & 0.97341 \pm 0.00021 & 0.04508^{+0.00075}_{-0.00528} \\ 0.00861^{+0.00021}_{-0.00037} & 0.04068 \pm 0.00138 & 0.999135^{+0.000057}_{-0.000018} \end{pmatrix}. \quad (1)$$

The precision of the individual elements is quite impressive. Also the fit of the so-called unitarity triangle shows a good overall consistency (figure from [7]).



Similar recent results can be found e.g. in [8, 9, 10]. Due to the success of the CKM-picture, Kobayashi and Maskawa were awarded in 2008 with the nobel price. In Section 2 we investigate a little more in detail the determination of the individual CKM-elements, while we discuss some hints for deviations from the standard model in Section 3. In Section 4 we conclude and give an outlook. We end with a *What to do list* in Section 5.

2 Status of the individual CKM elements

In this section we review very briefly the current status of our knowledge about the values of the CKM elements. More detailed reviews can be found e.g. in [3, 4, 7].

2.1 First row of the CKM Matrix

The CKM element V_{ud} is determined in the nuclear β -decay, in the neutron β -decay and in the pion β -decay [3, 11]. Data for the CKM element V_{us} stem from K_{l3} -decays, hadronic τ decays and semileptonic hyperon decays [3, 12, 13].

$$\begin{aligned} |V_{ud}| &= 0.97425 \pm 0.00022, \\ |V_{us}| &= 0.2254 \pm 0.0013. \end{aligned} \quad (2)$$

Both elements are quite precisely known, while we have different values of V_{ub} , depending on the extraction method: exclusive B -decays, inclusive B -decays (see e.g. the article of Kowalewski and Mannel in [3] for a list of references or [4]), from $B \rightarrow \tau\nu$ and from a global fit [7, 8].

$$\begin{aligned} |V_{ub}|^{\text{Exclusive}} &= 0.00351 \pm 0.00047, \\ |V_{ub}|^{\text{Inclusive}} &= 0.00432 \pm 0.00027, \\ |V_{ub}|^{B \rightarrow \tau\nu} &= 0.00510 \pm 0.00059, \\ |V_{ub}|^{\text{GlobalFit}} &= 0.00356 \pm 0.00020. \end{aligned} \quad (3)$$

The third value is taken from [14], the rest of the values is from [7]. Concerning the numerical value of V_{ub} several comments are appropriate: In particular the last two numbers differ quite sizeably, while the different values for the inclusive and exclusive extraction might hint to the fact that hadronic uncertainties (e.g. lattice, LCSR) are underestimated, see also [15]. There is also a new physics explanation for this discrepancy. Right-handed currents could lead to a deviation of the exclusive from the inclusive determination [16, 17]. New Physics in B_d -mixing might also enhance the global fit value of V_{ub} and therefore reduce the discrepancy with the value extracted from $B \rightarrow \tau\nu$. Due to these problems with V_{ub} Soni and Lunghi (see e.g. [9]) suggested not to use V_{ub} in the global fit.

Finally we would like to mention that, V_{ub} is actually of order λ^4 and not of order λ^3 in the Wolfenstein parameter $\lambda \approx 0.2254$ [18]

$$0.00356 = (0.2254)^{3.79}. \quad (4)$$

With all the values of the CKM elements from the first row one can test the unitarity of the CKM matrix

$$\sqrt{1 - V_{ud}^2 - V_{us}^2} = 0.00564_{-0.00564}^{+0.02669}. \quad (5)$$

A nice way to study the bounds on the unitarity of the CKM matrix is to investigate an extension of the standard model with an hypothetical fourth generation of fermions. If one assumes that V_{CKM4} is unitary, one gets the result that $V_{ub'}$ can still be larger than V_{ub} (see e.g. [19, 20, 21, 22, 23, 24] for some recent studies and also [25])

$$V_{ub'} < 0.04 . \quad (6)$$

Despite the impressive accuracy of the extracted values of the first row of the CKM matrix, it is still desirable to reduce the error of V_{us} further and to clarify the discrepancies in V_{ub} . Currently it is still not excluded that there exists a value of $V_{ub'}$, which is larger than V_{ub} .

2.2 Second row of the CKM Matrix

V_{cd} is measured [3] in semileptonic charm decays $D \rightarrow \pi l \nu$ and in charm production in neutrino interactions. V_{cs} is determined [3] in neutrino scattering, on-shell W decays and in semi-leptonic charm decays. V_{cb} is obtained from inclusive $B \rightarrow X_c l \nu$ decays and from exclusive $B \rightarrow D^{(*)}$ transitions (see e.g. the article of Kowalewski and Mannel in [3] for a list of references or [4]).

$$\begin{aligned} |V_{cd}| &= 0.230 \pm 0.011 , \\ |V_{cs}| &= 1.023 \pm 0.036 , \\ |V_{cb}|^{\text{Exclusive}} &= 0.03885 \pm 0.00047 , \\ |V_{cb}|^{\text{Inclusive}} &= 0.04115 \pm 0.00027 . \end{aligned} \quad (7)$$

Here the uncertainties are considerably larger than in the first row and again the inclusive determination of V_{cb} yields larger values than the exclusive one. Sometimes averages are used for V_{cb} , e.g.

$$|V_{cb}| = \begin{cases} (40.6 \pm 1.3) \cdot 10^{-3} & [3] , \\ (40.89 \pm 38 \pm 0.59) \cdot 10^{-3} & [7] . \end{cases} \quad (8)$$

To test the accuracy of the second row we again investigate a hypothetical 4th generation of fermions and assume that V_{CKM4} is unitary. One finds [19, 20, 21, 22, 23, 24] that $V_{cb'}$ can still be considerably larger than V_{cb}

$$V_{cb'} < 0.15 . \quad (9)$$

This is almost the size of the Wolfenstein parameter λ ! So clearly an improvement in the determination of the CKM elements of the second row is mandatory.

2.3 Third row of the CKM Matrix

Except for V_{tb} we do not have any direct information about the CKM elements of the third row. Single top production at the Tevatron [26] * gives

$$V_{tb} = 0.88 \pm 0.07 . \quad (10)$$

The precise values for V_{td} , V_{ts} and V_{tb} from Eq.(1) are obtained under the assumption of the unitarity of the 3×3 CKM matrix. Giving up this assumption the elements of the third row of the CKM matrix can deviate substantially from the values in Eq.(1). As an illustration we show the results of an analysis of the SM4, where it is assumed that the four dimensional CKM matrix is unitary, while the three dimensional matrix does not have to be unitary [19], similar results were obtained in [20, 21, 22, 23, 24]. In Fig. (1,2,3) we show the possible values of V_{td} , V_{ts} and V_{tb} in a complex plane and we compare it with the value from Eq.(1). The possible values of V_{td} , V_{ts} and V_{tb} were obtained by replacing the unitarity of the 3×3 CKM matrix by the unitarity of the 4×4 CKM matrix and by demanding that all direct measurements for the CKM elements, as well as bounds from FCNC and electro-weak precision observables are fulfilled.

For the last row of the CKM matrix still deviations of the order of 100% (for V_{td} and V_{ts}) from the standard values in Eq.(1) are possible. Here more precise determinations of V_{tb} (single-top, R -ratio) and any idea how to determine V_{td} and V_{ts} directly (see e.g. [28]) would be extremely helpful.

2.4 Another success of the CKM paradigm

Another success of the CKM picture represents the rare penguin decay $b \rightarrow s\gamma$ [29]. Experiment [4] agrees well with the NNLO theory prediction [30]

$$Br(b \rightarrow s\gamma)^{\text{Exp}} = (3.55 \pm 0.26) \cdot 10^{-4} , \quad (11)$$

$$Br(b \rightarrow s\gamma)^{\text{Theo}} = (3.15 \pm 0.23) \cdot 10^{-4} . \quad (12)$$

The experimental average uses numbers from BaBar, BELLE and CLEO. For a more comprehensive list of references see e.g. [31].

3 Hints for deviations from the SM

Besides the impressive success of the CKM picture, we see currently several hints for deviations of experiment from theory.

*After the conference D0 published [27] a measurement of the ratio ($R = |V_{tb}|^2/(|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2) = 0.90 \pm 0.04$, that gives a more tight bound on V_{tb} .

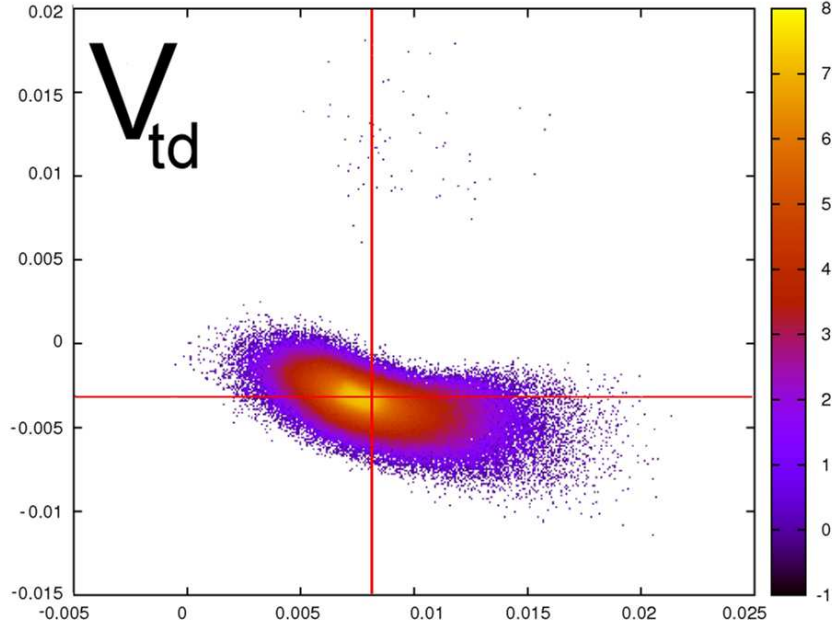


Figure 1: Allowed value of V_{td} in a complex plane. The value from Eq.(1) is denoted by the red lines.

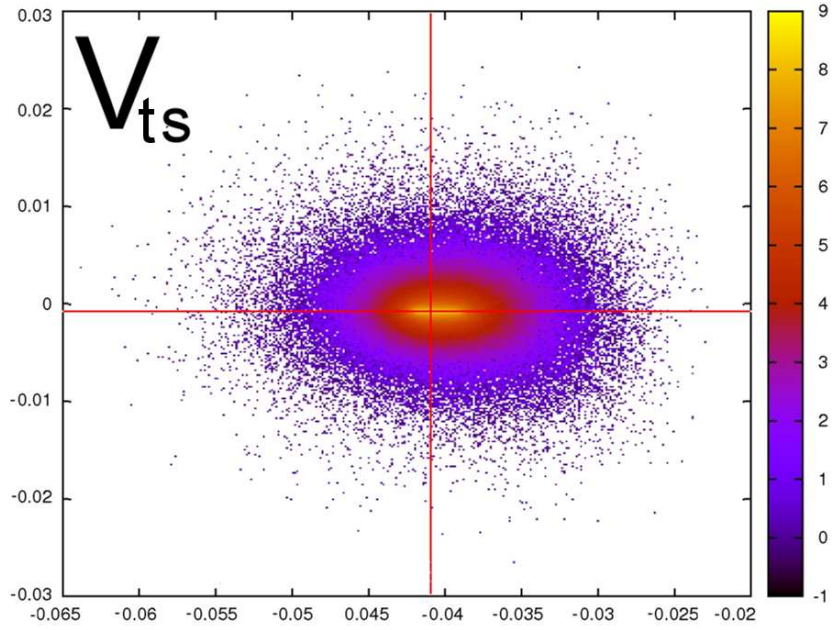


Figure 2: Allowed value of V_{ts} in a complex plane. The value from Eq.(1) is denoted by the red lines.

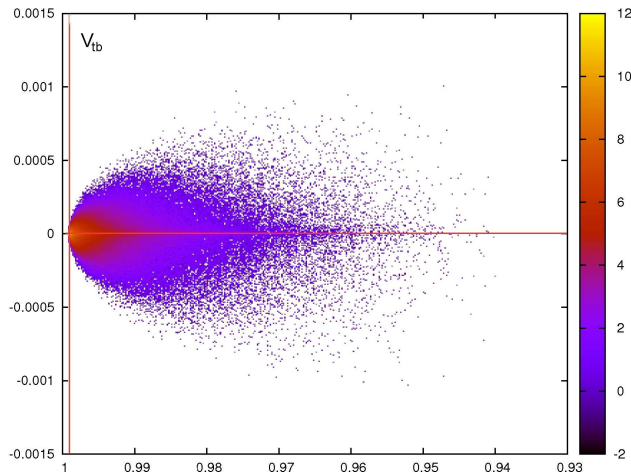


Figure 3: Allowed value of V_{tb} in a complex plane. The value from Eq.(1) is denoted by the red lines.

3.1 B_s -mixing

In the B_s system the dimuon asymmetry measured by the D0 collaboration [32], see also [33], is a factor of 42 larger than the standard model prediction [34].

$$A_{sl}^b := (0.506 \pm 0.043)a_{sl}^d + (0.494 \pm 0.043)a_{sl}^s, \quad (13)$$

$$A_{sl}^{b,SM} = (-0.023 + 0.005 - 0.006)\%, \quad (14)$$

$$A_{sl}^{b,Exp} = (-0.957 \pm 0.251 \pm 0.146)\%, \quad (15)$$

where a_{sl}^q is the semileptonic CP asymmetry in the B_q -system, see e.g. [35]. The SM prediction has been obtained by using the NLO-QCD calculations in [36], see also [37]. The statistical significance of the deviation is $3.2 \sigma^\dagger$, which triggered a lot of interest. At the time of writing this proceedings the first paper of [32] had approximately 150 citations within 15 months.

In terms of box diagrams the semileptonic CP-asymmetries are given by

$$a_{sl}^q := \frac{|\Gamma_{12}^q|}{|M_{12}^q|} \sin(\phi_q) \quad \phi_q := \arg\left(-\frac{M_{12}^q}{\Gamma_{12}^q}\right). \quad (16)$$

M_{12} is expected to be very sensitive to new physics, while Γ_{12} should be free of new physics contributions within the hadronic uncertainties (see e.g. [40]). Therefore

[†] After the conference D0 updated [38] the measurement. First the coefficients defining the dimuon asymmetry were updated: $A_{sl}^b = (0.594 \pm 0.022)a_{sl}^d + (0.406 \pm 0.022)a_{sl}^s$. Using also updated theory predictions for the mixing observables [39] one gets $A_{sl}^{b,SM} = (-0.023 \pm 0.004)\%$. For the new measurement instead of 6.1 fb^{-1} now 9.0 fb^{-1} of data were used. As expected [40] the central value went down, but the statistical significance increased to 3.9σ : $A_{sl}^{b,Exp} = (-0.787 \pm 0.172 \pm 0.093)\%$.

one can write in the presence of new physics model independently

$$M_{12}^q = M_{12}^{q,\text{SM}} \cdot |\Delta_q| e^{i\phi_q^\Delta} \quad \Gamma_{12}^q = \Gamma_{12}^{q,\text{SM}}. \quad (17)$$

Large new physics contributions to Γ_{12} would also affect the lifetime ratios of heavy hadrons - which agree relatively well, although there are large uncertainties due to the non-perturbative bag parameters, see e.g. [39, 41]) - and also the average number of charm quarks per b -decays n_c and $BR(b \rightarrow s + \text{no charm})$, see e.g. [42] for a mini-review.

Now one can write the general expression for semi leptonic CP asymmetries in the presence of new physics.

$$a_{sl}^q = \frac{|\Gamma_{12}^{q,\text{SM}}|}{|M_{12}^{q,\text{SM}}|} \frac{\sin(\phi_q^{\text{SM}} + \phi_q^\Delta)}{|\Delta_q|}. \quad (18)$$

Using the SM predictions for the mixing parameters [34, 39] and the bounds on Δ_q from [7] we get a maximal value of the dimuon asymmetry of

$$\begin{aligned} A_{sl}^b &= (0.594 \pm 0.022)(5.4 \pm 1.0)10^{-3} \frac{\sin(\phi_d^{\text{SM}} + \phi_d^\Delta)}{|\Delta_d|} \\ &+ (0.406 \pm 0.022)(5.0 \pm 1.1)10^{-3} \frac{\sin(\phi_s^{\text{SM}} + \phi_s^\Delta)}{|\Delta_s|}, \end{aligned} \quad (19)$$

$$A_{sl}^b \leq -4.8 \cdot 10^{-3}, \quad (20)$$

$$A_{sl}^b \leq -9.0 \cdot 10^{-3}. \quad (21)$$

For the bound in Eq.(20) we have taken the 1σ deviation of the SM predictions as well as the 1σ deviation of the fit result for Δ_q : ($\phi_d^\Delta = -12.9^\circ - 2.7^\circ$; $\phi_s^\Delta = -51.6^\circ - 9.7^\circ$; $|\Delta_d| = 0.747 - 0.0079$; $|\Delta_s| = 0.887 - 0.064$). In Eq.(21) we show for comparison the 3σ deviations in all parameters ($\phi_d^\Delta = -12.9^\circ - 7.0^\circ$; $\phi_s^\Delta = -90^\circ$; $|\Delta_d| = 0.747 - 0.17$; $|\Delta_s| = 0.887 - 0.12$).

The measured value of the dimuon asymmetry in Eq.(15) is about 1.66σ above the bound in Eq.(20). There are now 3 possibilities to explain this minor discrepancy:

1. The theory prediction for Γ_{12} has considerably larger uncertainties, than stated e.g. in [40]. For this reasoning several counter-arguments can be given:
 - The theoretical determination of lifetimes of heavy mesons relies on the same footing as the determination of Γ_{12} , see e.g. [41]. Within the hadronic uncertainties experiments and theory predictions agree well. However, this comparison is affected by sizeable uncertainties of the non-perturbative bag parameters of four-quark operators, that appear in the HQE. Here clearly a theoretical (= lattice) improvement would be very helpful, see e.g. [40] for more details.

- The higher order terms in the HQE converge well:
The current status of the theory is discussed in [40]. There it was shown, that the corrections to the leading term in the Heavy-Quark-Expansion (HQE) (i.e. α_s , subleading $1/m_b$ and lattice corrections to the vacuum insertion approximation for the non-perturbative matrix elements of the arising four-quark operators) give absolutely no hint for a non-convergence of the HQE. Their size is between 6% and 19%. This situation improved considerably compared to e.g. [43].
- Another possibility to check the robustness of the theory prediction for Γ_{12} is to use the exclusive approach for its determination. In the pioneering work of Aleksan et al. [44] this complementary approach gave

$$\frac{\Delta\Gamma_s}{\Gamma_s} \approx \mathcal{O}(0.15) , \quad (22)$$

which is in perfect agreement with the HQE determination [39]

$$\frac{\Delta\Gamma_s}{\Gamma_s} \approx 0.137 \pm 0.027 . \quad (23)$$

There was a recent update of the work of Aleksan et al. in [45], which again gives results that are in perfect agreement with the HQE determination of $\Delta\Gamma_s$.

Besides these strong arguments for the validity of the HQE approach for Γ_{12} , one also has to keep in mind, how large the effects on Γ_{12} would have to be, to explain the above 1.66σ discrepancy:

- Assuming that there is new physics in M_{12} and using for the size of the new physics effects the fit results from [7] one would need an enhancement of $|\Gamma_{12}|$ of about 200% to obtain the central value of the dimuon-asymmetry.
- Assuming that there is no new physics in M_{12} and all the discrepancy is due to a failure of the HQE one would need an enhancement of $|\Gamma_{12}|$ of about 4100% (3300% for the updated measurement of the dimuon asymmetry from D0) to obtain the central value of the dimuon-asymmetry.

So it seems very unplausible, that a failure of the HQE is responsible for the minor discrepancy in the dimuon asymmetry. Nevertheless a measurement of $\Delta\Gamma_s$ in the near future at LHCb will be very important to settle this issue.

2. New physics contribution to Γ_{12} .

Due to the arguments given below Eq. (18) we consider it also impossible that new physics can give contributions of the order of 200% - 3300%. New physics effects of the order of the hadronic uncertainties are probably not yet excluded.

3. The 1.66σ discrepancy is just a statistical fluctuation.

This seems currently to be by far the most obvious explanation. Actually the new D0 value for the dimuon asymmetry [38] shrank - the discrepancy is now 1.5σ .

To clarify my point of view: I do not consider the effect itself seen at D0 to be a statistical fluctuation, only the high central value. Even if the actual dimuon asymmetry is below the bound in Eq.(20) this would correspond to a very large new physics effect. As will be discussed below there are more indications for new physics acting in the B_s -system, that are consistent with a large dimuon asymmetry (and also with the sign). Of course this point of view will change if the central value stays, when the errors are reduced. But compared to 1.5 standard deviations I consider the above arguments for a validity of the theory approach to be much stronger.

Another hot topic in the B_s -mixing system is the angular analysis of the decay $B_s \rightarrow J/\psi\phi$. This decay is investigated at TeVatron (CDF and D0) [46] and LHCb [47]. There are also some small hints for deviations from the SM, which are compatible with the sign and size of the dimuon asymmetry. From the angular analysis one gets $\Delta\Gamma_s$ and $S_{\psi\phi}$, which is defined as

$$S_{\psi\phi}^{\text{SM}} = \sin\left(2\beta_s - \phi_s^\Delta - \delta_s^{\text{Peng,SM}} - \delta_s^{\text{Peng,NP}}\right) . \quad (24)$$

Neglecting penguins, one gets in the standard model

$$S_{\psi\phi}^{\text{SM}} = 0.0036 \pm 0.002 . \quad (25)$$

The new physics fit from [7] gave however

$$S_{\psi\phi} = 0.78^{+0.12}_{-0.19} . \quad (26)$$

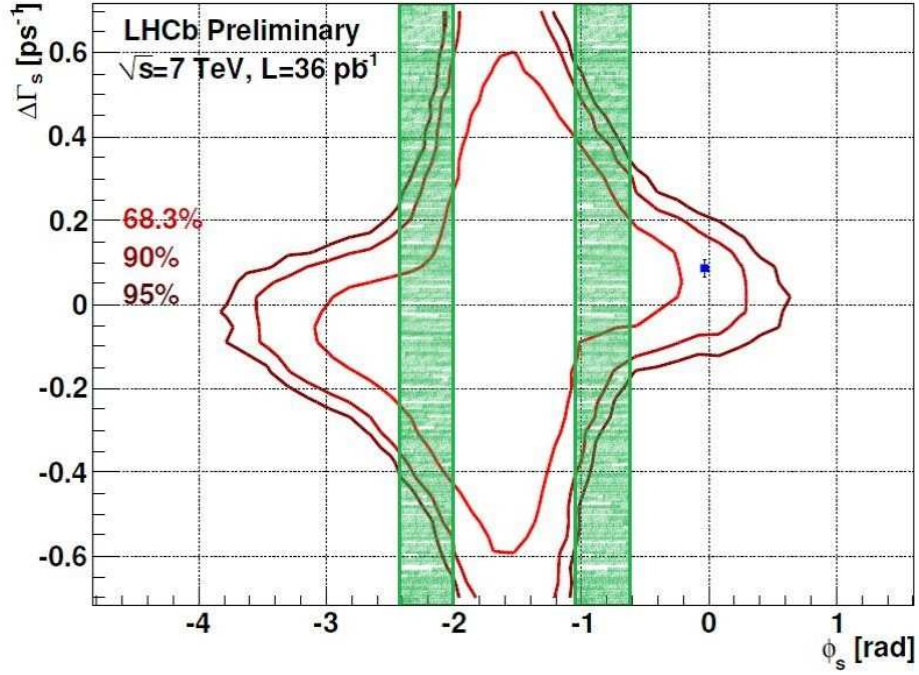
The history of these measurements, which deviated originally even more from the SM prediction is presented in [46]. After the conference D0 updated its analysis with 8.0 fb^{-1} of data [48], with the result

$$\phi_s^{J/\psi\phi} =: -2\beta_s + \phi_s^\Delta + \delta_s^{\text{Peng,SM}} + \delta_s^{\text{Peng,NP}} \quad (27)$$

$$= -0.55^{+0.38}_{-0.36} , \quad (28)$$

$$\Delta\Gamma_s = 0.163^{+0.065}_{-0.064} \text{ ps}^{-1} . \quad (29)$$

Here we will soon get a definite answer from LHCb, whether a large NP contribution exists in $S_{\psi\phi}$ or not. The LHCb status with the 2010 data [49] is given in the following figure.



The blue point denotes the SM value. In green the fit result for the new physics phase ϕ_s^Δ from [7] is shown under the assumption that penguins are negligible. The coming result from LHCb will probably have about 10 times more statistics. Finally we would like to make a comment on the often used relation

$$a_{sl}^s = -\frac{\Delta\Gamma}{\Delta M} \frac{S_{\psi\phi}}{\sqrt{1 - S_{\psi\phi^2}}} \cdot \delta, \quad (30)$$

with

$$\delta = \frac{\tan(\phi_s^{\text{SM}} + \phi_s^\Delta)}{\tan(-2\beta_s^{\text{SM}} + \phi_s^\Delta + \delta_s^{\text{peng,SM}} + \delta_s^{\text{peng,NP}})}. \quad (31)$$

Typically it is assumed that for a large new physics phase in mixing ϕ_s^Δ , δ is closed to one and can be neglected. A more detailed analysis in [40] shows however, that $\delta = 1$ is strongly violated. Therefore Eq.(30) without δ can not be used to eliminate the theory prediction for Γ_{12} . Instead it might be used to determine the size of penguin contributions to the decay $B_s \rightarrow J/\psi\phi$, which is also an important task.

3.2 B_d -mixing

Due to the increased precision in experiment and theory in the last years hints for new physics were also found in the golden plated mode $B_s \rightarrow J/\psi K_s$ [50]. Comparing the direct measurement [51] of $\sin(2\beta)$ with the indirect determination from the CKM fits [7] we get

$$\sin(2\beta)^{\text{Exp.}} < \sin(2\beta)^{\text{Fit}} , \quad (32)$$

$$0.678 \pm 0.020 < 0.831_{-0.030}^{+0.013} , \quad (33)$$

$$\beta = (21.4 \pm 0.8)^\circ < (28.09_{-1.49}^{+0.7})^\circ . \quad (34)$$

This discrepancy was pointed out first in [52] and then in [53], it is currently seen by all CKM-fitting groups, with a similar statistical significance:

Reference	Group	Deviation
1102.3917 [10]	Laiho, Lunghi, Van de Water	$2.5 - 3.3 \sigma$
1010.6069 [9]	Lunghi, Soni	3.3σ
1010.5089 [8]	UTfit	2.6σ
1008.1593 [7]	Lenz, Nierste, CKMfitter	2.8σ

3.3 More hints for deviations

3.3.1 $B \rightarrow \tau\nu$

The discrepancy in $B \rightarrow \tau\nu$ was already mentioned in the discussion of V_{ub} . The measured branching ratio [54] is considerably larger than the theoretically expected one. If this tension is due to new physics, it might be triggered by direct contributions to the decay $B \rightarrow \tau\nu$ (e.g. Two-Higgs-Doublet model) or by new physics in B_d mixing, which results in a different value for V_{ub} .

3.3.2 ϵ_K

The discrepancies in the CKM fits mentioned above in the B_d -section might also be due to new physics acting in ϵ_K [53]. ϵ_K depends strongly on V_{cb} (fourth power) as well as on the value the non-perturbative bag-paramter \hat{B}_K . Depending on the central

values and errors used for \hat{B}_K one gets different discrepancies between experiment and standard model prediction for ϵ_K , e.g.

Reference	Group	\hat{B}_K	Deviation of ϵ_K
1102.3917 [10]	Laiho, Lunghi, Van de Water	0.736 ± 0.020	1.9σ
1008.1593 [7]	Lenz, Nierste, CKMfitter	0.724 ± 0.067	0.5σ

A nice comparison of the different methods used by the different groups to determine lattice averages is given in [55].

3.3.3 $B \rightarrow K^{(*)}ll$

The status of the decays $B \rightarrow K^{(*)}ll$ was discussed in [56]. There were some hints for discrepancies between the data from BaBar, Belle and CDF and the standard model expectation. After the Conference LHCb [57] and CDF [58] announced more precise measurements of $B \rightarrow K^{(*)}ll$, which are consistent with the standard model predictions, see e.g. [59]. Here still more data are needed to draw some final conclusions.

3.3.4 $B_s \rightarrow \mu\mu$

The very rare decay $B_s \rightarrow \mu\mu$ gives strong constraints on many extensions of the standard model. The experimental situation was discussed in [60] for the TeVatron and in [61] for LHC. After the conference CDF announced a first two-sided bound on the rare decay $B_s \rightarrow \mu\mu$ [62]

$$Br(B_s \rightarrow \mu\mu) = (18_{-9}^{+11}) \cdot 10^{-9} \quad (35)$$

Updating the SM prediction (see e.g. [63]) we obtain with the input parameters from [7]

$$Br(B_s \rightarrow \mu\mu) = (3.0 \pm 0.4) \cdot 10^{-9} . \quad (36)$$

If we in addition assume that there is now new physics in ΔM_s we can get rid of the large uncertainties due to the decay constant and get the very precise prediction

$$Br(B_s \rightarrow \mu\mu) = (3.1 \pm 0.1) \cdot 10^{-9} . \quad (37)$$

The central value of the experimental number from CDF is a factor of 6 larger than the theory prediction, but the statistical significance of the deviation is less than 2σ . LHCb [64] and CMS [65] presented new results for $B_s \rightarrow \mu\mu$ at the EPS conference. They did not confirm the signal of CDF, but there is still a lot of room for new physics.

$$\text{CMS: } Br(B_s \rightarrow \mu\mu) < 19 \cdot 10^{-9} \quad 95\%C.L. , \quad (38)$$

$$\text{LHCb: } Br(B_s \rightarrow \mu\mu) < 15 \cdot 10^{-9} \quad 95\%C.L. . \quad (39)$$

For the B_d -decay the following bounds hold now

$$\text{CMS: } Br(B_d \rightarrow \mu\mu) < 4.6 \cdot 10^{-9} \quad 95\%C.L. , \quad (40)$$

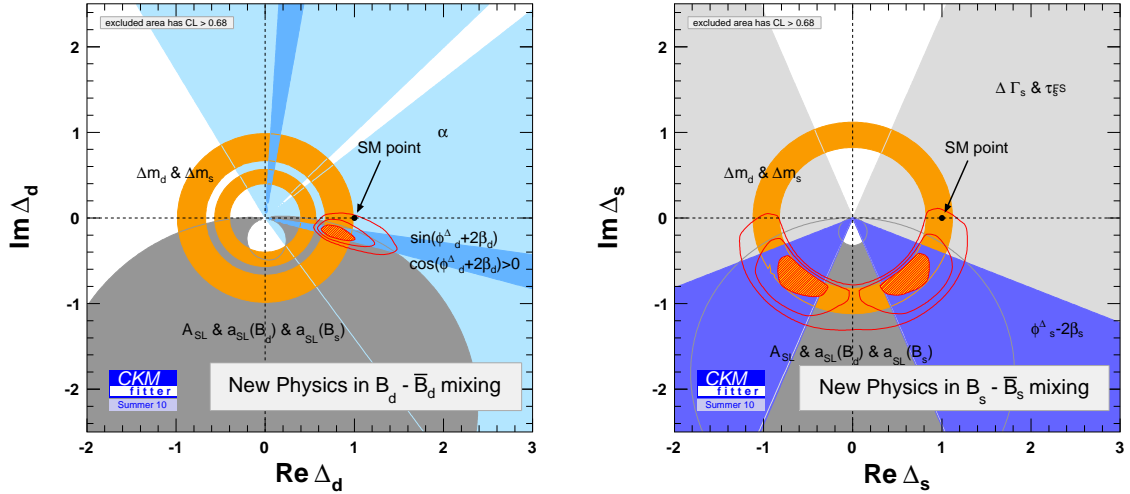
$$\text{LHCb: } Br(B_d \rightarrow \mu\mu) < 5.2 \cdot 10^{-9} \quad 95\%C.L. . \quad (41)$$

3.3.5 Hadronic B decays

Hadronic decays were discussed in [66].

3.4 Combining the hints

In [7] a model independent fit of new physics acting only in the neutral meson mixing systems was performed. Besides the usual parameters, now also the parameters Δ_d and Δ_s defined in Eq.(17) were fitted. The results are shown in the following two figures:



The standard model corresponds to $\Delta_q = 1$. The fit shows however that $\text{Im } \Delta_d = 0 = \text{Im } \Delta_s$ is excluded with 3.8 standard deviations. Including the the new D0 dimuon result, the SM would probably be excluded with more than 4 standard deviations.

4 Conclusion and Outlook

Soon we will get much more data, in particular from the LHC, but also from Tevatron and the B-factories. A first part of this new data was already made public after FPCP2011.

We will know definitely, whether $S_{\psi\phi}$ is really large and whether the current hints

for large new physics effects in B -mixing are real. We also will soon know how large $\Delta\Gamma_s$ is. This measurement will have a big impact on our understanding of the theory methods used to determine Γ_{12} . Moreover we will gain more information on the semileptonic CP asymmetries. Tevatron might still improve on the dimuon asymmetry A_{sl}^b , the B-factories, Tevatron and LHC might enhance our knowledge about the individual semi leptonic CP asymmetries $a_{sl}^{s,d}$ and LHCb will have information on $a_{sl}^s - a_{sl}^d$. The data and bounds on the rare decays $B \rightarrow K^{(*)}ll$ and $B_s \rightarrow \mu\mu$ will be improved. Even if the parameter space for new physics effects was shrinking recently, there is still room for large new effects. Tevatron and LHC will also provide more data for charm mixing [67]. Here it is still not clear how well our theoretical tools from the beauty sector work [68]. The D -system is also well suited to search for new physics effects, see e.g. [69]. Also rare Kaon decays like $K \rightarrow \pi\nu\nu$ [70] or lepton flavor violating decays like $\mu \rightarrow e\gamma$ [71] will play a crucial role.

Besides identifying the new physics effects in certain observables or in a combined fit, the next important question will be *How to interpret this data?* [72]. This can be done within certain models for extensions of the standard model (see the plethora of papers on the arXiv) or model independently. Since the CKM picture works very well, the framework of minimal flavor violation (MFV) [73] seems to be very promising. Nevertheless one should keep in mind that there are also viable counter examples for MFV like the SM4: due to possible cancellations between $\delta V_{td,s,b}$ and the t' -loop, there can still be effects of $\mathcal{O}(100\%)$ in B -mixing, which are consistent with the CKM fits, see e.g. [19, 20, 21, 22, 23, 24]. A very promising approach to interpret the hints for new physics is to study correlations among different observables in different models, as strongly advocated by the group of A. Buras.

In order to make full use of the coming data, there is however also a lot of basic work (i.e. no model building...) to be done. We finish therefore with a *What to do list*.

5 What to do list

We have to improve our current knowledge of the CKM matrix:

- First row: Understand the origin of the different results for V_{ub} and improve the accuracy in V_{us} .
- Second row: Improve the accuracy in V_{cs} and V_{cb} .
- Third row: Improve the accuracy in V_{tb} and find a way to measure V_{td}, V_{ts} .

We also have to improve our understanding of the machinery to describe the mixing systems theoretically:

- Test of the HQE with lifetimes of heavy hadrons.

- τ_{B^+}/τ_{B_d} and τ_{B_s}/τ_{B_d} fit well within the hadronic uncertainties and we have currently no hints for deviations from the HQE.
- To improve, precise non-perturbative matrix elements for the arising 4-quark operators are urgently needed.
- There are also some perturbative improvements of lifetime predictions missing, like the full NLO-QCD calculation of the Λ_b lifetime.
- More precise theoretical predictions for mixing observables.
 - Precise decay constants and Bag parameter for ΔM
 - Additional Bag parameters at dimension 6 and 7 for Γ_{12}
 - α_s/m_b corrections for Γ_{12}
 - α_s^2 corrections for Γ_{12}
- Theoretical predictions for charm mixing observables
Push HQE to its limits.
- Try to improve the exclusive approach as a cross-check, see e.g. [45].

Finishing these tasks will enable us to make full use of the exciting times lying ahead of us.

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